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Modeling criteria for extraction regime transitions for microscale in-situ vapor extraction applications

Saran Salakij, James A. Liburdy *, Deborah V. Pence

Mechanical Engineering, Oregon State University, Corvallis, OR, USA

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ABSTRACT

A major detriment of two-phase microscale flow systems is a significantly large pressure drop. For flow boiling the potential for flow instabilities is also a major concern. Both disadvantages may be suppressed by extracting vapor through a hydrophobic porous wall of the channel as a means to reduce the channel vapor fraction. The vapor extraction may occur as different regimes either as evaporation, bubble extraction or a combination of both. In the design of vapor extraction systems, it is important to accurately predict extraction rates, different extraction regimes, and the effect of extraction on the heat transfer and channel flow conditions. This study focuses on two parts: the development of physic-based models for the transition criteria among (i) the extraction mechanism regimes, and (ii) the extraction flow regimes for microscale flow boiling. The identification and conditions for the various extraction regimes are discussed and criteria for transition are developed based on physical concepts. Six potential extraction mechanism regimes are identified: (a) no extraction, (b) evaporation, (c) bubble extraction, (d) bubble extraction with partial liquid blockage, (e) bubble extraction with evaporation, and (f) liquid breakthrough. Based on the criteria for the extraction mechanism regimes, the rate of vapor extraction is modeled and used to analyze the effects of vapor extraction on the dynamics of two-phase flow boiling. The results show six extraction flow regimes for two-phase flow boiling: (i) single-phase evaporation, (ii) two-phase evaporation – bubble collapse, (iii) full extraction – stable, (iv) full extraction – unstable, (v) partial extraction – stable and (iv) partial extraction – unstable.

1. Introduction

Due to the increased development of high performance electronic devices in the last few decades, as well as their miniaturization, the large increase in heat dissipation per unit volume has become a major concerned. Cooling technologies utilizing two-phase microscale heat sinks have advantages due to high surface to volume ratio and large heat transfer coefficients. For two-phase flow boiling, an additional advantage is the relatively small streamwise temperature variation compared with single-phase methods. However, a major issue of flow boiling in microchannels is a correspondingly large pressure drop and accompanying flow instabilities [1,2]. A large pressure drop can lead to large temperature variations along the flow in the two-phase regime. Also, the large pressure drop and thermal oscillations due to flow instabilities may lead to severe mechanical vibration and dry-out [1].

Numerous investigators [2–10] have developed channel modifications as a means to suppress instabilities, which may be categorized into three main groups: (i) use of an inlet restrictor, (ii) application of engineered nucleation sites, and (iii) use of an expanding channel. The first group [2–4] stabilizes flow boiling by placing a flow restrictor at the inlet to decrease the reverse vapor flow. However, the drawback of this method is a large increase in the pressure drop of the system [5]. The second group [5–7] fabricates artificial nucleation sites on the channel walls. This reduces the required superheat surface temperatures and thereby reduces the rapid expansion of the bubble. The third group [5,8–10] uses an increasing flow cross sectional area along the flow direction causing bubbles to expand downstream rather than upstream, leading to less vapor reverse flow.

An alternative approach using in-situ vapor extraction, which has shown to potential stabilize flow boiling, has been investigated by Salakij et al. [11]. The goal of in-situ vapor extraction is to locally extract the generated vapor from the channel through a hydrophobic porous wall so as to reduce or control the vapor fraction inside the channel. In a thermal management application the extracted vapor would most likely be condensed and reused as a

* Corresponding author. Tel.: +1 541 737 7017.
E-mail address: james.liburdy@oregonstate.edu (J.A. Liburdy).

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Nomenclature

A	area
Bo^*	modified Boiling number, $Bo^* = \frac{q}{\dot{m} i_{lv}}$
Ca_v	Capillary number, $Ca_v = \frac{\mu_l j_v}{\sigma}$
C_b	dimensionless parameter for minimum wall superheat requirement
C_w	rapid wave growth factor
c_p	specific heat
d_p	equivalent membrane pore size
D_h	hydraulic diameter
Fr^*	modified Froude number, $Fr^* = \sqrt{\frac{\rho_v}{\rho_l - \rho_v}} \frac{j_v}{\sqrt{gH \cos\alpha}}$
g	acceleration due to gravity
G	mass flux
H	channel depth
H_l	liquid level height
h	heat transfer coefficient
i	enthalpy
i_{lv}	heat of vaporization
Ja	Jacob number, $Ja = \frac{\rho_l}{\rho_v} \frac{c_{p,l} \Delta T_{sub}}{i_{lv}}$
j	superficial velocity
k	thermal conductivity
$\dot{m}$	mass flow rate
N_{extr}	extraction number, $N_{extr} = \dot{m}_{extr}/\dot{m}_{in}$
Nu	Nusselt number
P_{extr}	extraction absolute pressure
$\wp_w$	wetted perimeter
q	heat input rate
q''	heat flux
S	contact surface per unit length
St	stability parameter
T	temperature
u	velocity
v	specific volume
W	channel width
We	Weber number, $We = \frac{G^2 D_h}{\rho_l \sigma}$
X	Lockhart–Martinelli parameter
x	thermodynamic equivalent quality
x^*_{out}	ideal exit quality without vapor extraction, $x^*_{out} = \frac{\frac{q}{\dot{m}_{in}} - c_{p,l} \Delta T_{sub,in}}{i_{lv}}$
Y	dimensionless parameter presented in [25], $Y = \frac{(\rho_l - \rho_v) g \sin\beta}{(dP/dz)\vert_v}$

Greeks

α	void fraction
α_c	channel aspect ratio, $\alpha_c = W/H$
β	channel inclination angle
δ_c	surface roughness
δ_t	thermal boundary thickness, $\delta_t = k_l/h_{lo}$
ΔP_{extr}	extraction pressure differential
ΔT_{sat}	wall superheat, $\Delta T_{sat} = T_w - T_{sat}$
ΔT_{sub}	subcooling, $\Delta T_{sub} = T_{sat} - T_b$
θ_c	contact angle
θ_d	half-diverging angle
κ	specific membrane permeability
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension

Subscripts

b	bulk
bub	bubble
c	cross-sectional
$extr$	extraction
$heat$	heated
i	liquid–vapor interface
in	Inlet
l	liquid phase
lo	all-liquid
mem	membrane
ONB	onset of nucleate boiling
out	outlet
sat	saturation
v	vapor phase
w	wall

coolant, allowing for efficient condenser design having only vapor inlet flow. Salakij et al. [12] combined a channel with an expanding cross section with vapor extraction and shows significant improvement to the allowable stable heat flux.

Apart from the ability to stabilize the flow, several studies suggest that in-situ vapor extraction also has the potential to reduce the system pressure drop while maintaining the benefit of enhanced heat transfer [13–18]. Apreotesi et al. [13,14] experimentally investigated flow boiling of water through a fractal-like branching microchannel network with in-situ vapor extraction, showing a decrease in the system pressure drop with increasing extraction pressure differential. A later work by Salakij et al. [18], using a one dimensional predictive model validated against the experimental results obtain in [13,14], shows up to a 70% decrease in the overall pressure drop. Moreover, the bulk fluid temperature within the channel was shown to decrease indicating the potential of in-situ vapor extraction to decrease the overall operating temperature of the device. David et al. [16] investigated two-phase flow in parallel microchannels with vapor venting, where the flow and venting channels were separated by hydrophobic porous membrane. Their results show a significant decrease in pressure drop. The computational model of the vapor-venting process studied by Fang et al. [17] also confirmed this result showing that vapor-venting helps suppress local dry-out in microchannels.

In order to fully utilize the potential of in-situ vapor extraction for two-phase flow, it is necessary to understand the effects of vapor extraction on heat transfer and flow conditions. The effects of vapor extraction are directly related to the vapor extraction mass flow rate. A number of studies [12–19] have predicted the vapor/gas average velocity, V_{extr}, transport across the membrane based on Darcy's law as:

$$V_{extr} = \frac{\kappa}{\mu_v} \nabla P_{extr} \tag{1}$$

Note that all symbols are identified in the Nomenclature. This model may indeed require added complexities to be accurate for this application. For example, Salakij et al. [12,18] related vacuum membrane distillation to vapor extraction and included evaporation effects on the vapor extraction where the evaporation rate is based on the local vapor pressure gradient across the membrane. Cappello et al. [20] used the dusty gas model, as a general form of Darcy's law, with added effects of membrane compaction to successfully predict gas and superheated vapor transport through the membrane.

Several studies suggest that two-phase hydrodynamic conditions near the membrane affect vapor extraction. Alexander and Wang [21] studied vapor separating from a two-phase microscale flow through a hydrophobic porous plate, called a breather. A